

Application of Dredge Monitoring Systems to Dredge Contract Administration Quality Assurance

PURPOSE: Monitoring technology is available for providing dredge process data to dredge contract administrators during the course of a dredging contract. The U.S. Army Corps of Engineers (USACE) contracts out more than 80 percent of all dredging under their jurisdiction. Presently, Corps District offices have taken on more of a contract administration role rather than a technical "hands on" role for insuring that the nation's waterways remain open and are navigable. Although Corps inspectors are generally aboard the contractor's dredge during the dredging, the contract administrator does not have direct access to dredge process data for evaluating the contractor's performance. This technical note describes dredge-monitoring systems designed to provide contract administrators with dredge process data for evaluating dredge productivity, efficiency, and overall performance.

BACKGROUND: Generally, there are two types of dredging contracts: a lease dredge contract, and a yardage contract. Payment of the lease dredge contract is based on an estimation of the time required to remove an estimated amount of sediment from the project area. The primary consideration for the cost of this work is the production capability of the dredge plant in removing cubic yards of in place material per hour, and the hourly cost of the plant. The contracting officer is responsible for insuring that the contracting dredge operates efficiently and maintains a reasonable production rate over the project duration to insure that the terms of the contract are met. Typically, the progress of the contractor dredge is gauged by post-dredging surveys which indicate if the channel has been cleared to project depth. Potential disputes arise between the contractor and the Corps concerning the rate the work is performed, i.e., if the dredging extends past the time specified in the contract for completion of the job. In some cases, changing site conditions, such as sediment variations or adverse weather or project site conditions will affect the work performance rate. If conditions are encountered that affect the ability of the contractor to perform as specified in the contract the contracting officer should be aware of these conditions within a reasonable time to adjust the terms of the contract, and prevent costly litigation. Additional monitoring tools are needed by contract administrators to judge if the dredge is operating efficiently and maintaining a reasonable production rate.

The cubic yard contract provides payment to the contractor based on pre- and post-dredging surveys. In this contract, the dredge contractor is paid by the volume of material removed, with the price per unit volume negotiated in the contract. This price reflects the contractor's operating costs as well as the profit margin. The primary consideration for this type contract is the accuracy and dependability of the pre- and post-dredging surveys. The pre-dredging survey provides an estimate of the material to be removed. In river systems, the river bed is constantly moving and changing, sometimes drastically affecting the shoaling rate. During the time elapsed between the pre-dredging survey and the contract bid and award, significant shoaling can occur, thus the pre-dredge survey will underestimate the amount of material to be removed. Also, if the post-dredge survey is not performed in a timely manner, additional shoaling can occur, thus again underestimating the amount

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of material removed. In the past, these conditions have resulted in legitimate claims by contractors. The contracting officer needs a source of additional dredge process data beyond post-dredging surveys and the typical dredge logs provided by the contractor to evaluate the productivity and efficiency of the dredge.

MONITORING SYSTEM COMPONENTS: Dredge monitoring systems contain three components: an active data gathering component consisting of sensors for measuring dredge process parameters; a data acquisition system for acquiring and storing raw data; and a post-processing component for reducing the data into a useable form for interpretation. Monitoring systems and their associated components are described for both pipeline and hopper dredges.

Pipeline Dredge. The productivity of a pipeline dredge, such as a cutterhead dredge, is dependent on variables such as sediment characteristics, suction line losses, cutface limitations, dredge advance, and discharge line losses. Variables such as digging depth and friction losses in the suction line limit the ability of the dredge to pick up sediment, whereas the cutface limits the amount of material available to the dredge. In this sense, the cutterhead dredge is suction line limited, i.e., in that suction line losses and cutface limitations will dictate production. In addition, cutterhead dredges must be capable of generating high discharge heads for pumping long distances. Therefore, the cutterhead dredge is also discharge limited, in that it must have the horsepower available to transport the solids picked up by the suction line. To properly evaluate the productivity and efficiency of a cutterhead dredge, it is therefore necessary to acquire dredge process data, which provides information on both the suction and discharge performance of the dredge.

Dredge process monitoring for quality assurance involves two stages. The pre-dredge stage consists of analyzing the capability of the proposed dredge plant during the bidding process. This is a theoretical analysis that evaluates the suction and discharge limitations of the dredge given project site constraints. The second stage involves acquiring real-time dredge process data while the dredge is working to monitor dredge productivity and efficiency.

Pre-Dredge Analysis of Dredge Capability. When contractors submit bids for the dredging job, the dredge plant design should be evaluated to insure that it can nominally meet the performance requirements for the project. This involves a theoretical evaluation of its capabilities. The contract administrator can utilize dredge computer models to evaluate the theoretical performance of the dredge. Project pre-dredge survey data will provide an estimate of the cutface available to the dredge. The efficiency of the dredge is dependent on the method used for advancing the dredge through the cut. A walking spud arrangement has an approximate cycle efficiency of 50 percent while a spud carriage arrangement has an approximate efficiency of 75 percent (Turner 1984).

Based on this information, and the design and setup of the dredge plant, the dredge capability can be approximated (Scott 1998). Inputs to the model include digging depth, suction line diameter and length, discharge line diameter and length, in situ sediment density, water density, pump efficiency, bank height factor, and cycle efficiency among other dredge parameters. A number of these models exist in government and industry that are capable of performing these calculations. These models can tell the user the approximate average slurry density that the dredge should be capable of maintaining over the project when the cutterhead is engaged in the material, and also over the entire cycle which includes the inefficiencies caused by the advance of the dredge. The contract

administrator can use this model in conjunction with the actual monitoring data to insure that the dredge is meeting minimal production requirements.

Another component essential to the pre-dredge analysis is the dredge pump characteristic curve, which details the relationship between pump discharge head, discharge, efficiency, horsepower, and pump speed. Data generated from the theoretical dredge model can be used in conjunction with the pump curve to determine the approximate pump operating point during the project. This is essential to insuring that the pump operates above the minimum flow rate for settling of solids in the pipeline and that horsepower limitations are not a controlling factor.

Figure 1 is an example of the pump curve for a 0.68- by 0.68-m- (27- by 27-in.-) dredge pump with a 2,134-m- (7,000-ft-) long discharge line at the maximum pump speed, 575 rpm. The maximum pump power available is 2,237 kW (3,000 hp). The system head requirement curves generated from a dredge performance model are plotted on the pump curve. These curves represent water in the pipe, 5 percent by volume solids slurry, 10 percent by volume solids slurry, and 18 percent by volume solids slurry. The sand size is 0.16 mm (0.0006 in.), with a critical velocity of deposition in the 0.68-m (27.0-in.) pipe of about 3.66 m/sec (12.0 ft/sec) or 81,052 L/min (21,414 gpm).

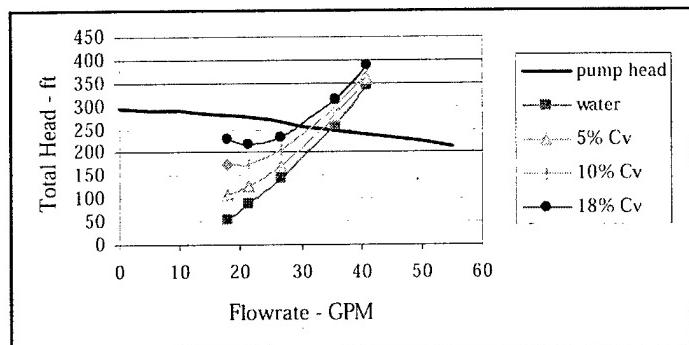


Figure 1. Pump curve for a 0.68- by 0.68-m- (27- by 27-in.-) dredge pump with a 2,133.6-m- (7,000-ft-) discharge line

The pump will operate at the intersection of the system curves and the pump curve. The 18 percent solids system curve intersects the pump curve at a head of about 255 ft of water and a discharge of approximately 113,550 L/min (30,000 gpm) (5.12 m/sec (16.8 ft/sec) flow velocity in the pipeline). This dredge is capable of pumping the maximum concentration of solids (18 percent) at a velocity above the minimum velocity required to prevent deposition in the pipeline. Dredge production is approximately 1,618 m³/hr (2,115 yd³/hr) with 2,152 kW (2,886 hp) required.

In summary, dredge performance can be estimated using the dredge performance model in conjunction with the pump characteristics curve. The model provides estimated values of slurry density (solids concentration) and dredge production during each phase of the dredging cycle. These values can be compared to the real-time slurry density and velocity data acquired from the production meter on the dredge.

Dredge Process Data to Monitor Dredge Performance. A number of monitoring systems can be used on a pipeline dredge to assist in maintaining dredge production (Pankow 1989). The most common instrumentation for monitoring solids transport are the velocity meter and slurry density gauge. The velocity of the dredged slurry in the pipeline can be measured with a variety of types of flow meters. The slurry velocity data alone is not descriptive of the efficiency of the dredge plant, but when evaluated in conjunction with the slurry density measurement, a relative measure of dredge production rate can be made.

The slurry density is typically measured by a nuclear density source located on the dredge discharge pipeline. The slurry density measurement provides a complete record of the dredging operation. It provides data on the average slurry density when the suction head is engaged in material, the average slurry density during the overall dredging cycle (for a cutterhead dredge), and the cycle and overall dredge efficiency. The following section details how each part of the dredge cycle can be analyzed to evaluate dredge performance during the project.

Dredge Cycle Analysis. For the purpose of this analysis, the cutterhead dredging cycle consists of when the dredge swings into the material, completes the swing, and advances the dredge. When the dredge is engaging the material, solids entrainment is limited by suction line losses and cutface height. The average density while the cutterhead is engaged in the material is calculated to be:

$$\rho_{mat} = \frac{\sum_0^N \rho_s}{N_{cyc}} \quad (1)$$

where

ρ_{mat} = the average slurry density while in material in g/cm³

ρ_s = measured slurry density in g/cm³

N_{cyc} = number of data points

This represents the maximum capability of dredge in removing and transporting solids given project constraints such as the bank height limitation and flow conditions. The cutface height generally dictates the maximum amount of material that can be removed when the cutterhead is engaging material. If the cutface height is small, which is typical for maintenance dredging projects, the solids content of the slurry conveyed by the dredge will be reduced. As a rule, if the bank height is on the order of the diameter of the cutterhead or greater, ample material will be available for loading the suction pipe, and therefore maximizing solids content and dredge production.

The overall average cycle slurry density represents an average of the slurry density when the cutterhead is engaged in material, and when the dredge is advancing, at which time only water is being pumped. This cycle overall average density is represented by:

$$\rho_{cyc} = \frac{\sum_0^N \rho_s}{N} \quad (2)$$

where

ρ_{cyc} = the average slurry density over the cycle in g/cm³

N = number of data points

This represents the overall slurry density transported to disposal. It is a function of suction line head losses, cutface height, and cycle efficiency.

The cycle efficiency is defined as the ratio of the average solids component of the slurry over the entire cycle to the average solids component of the slurry when the dredge is engaging the material. This efficiency is computed as:

$$C_{eff} = \frac{\rho_{cyc} - 1}{\rho_{mat} - 1} \quad (3)$$

The cycle efficiency can also be presented in terms of time as:

$$C_{eff} = \frac{T_{sol}}{T_{tot}} \quad (4)$$

where

T_{sol} = the time pumping solids

T_{tot} = the total time (time in solids and water)

The production rate for the dredge is calculated by the following equation:

$$PRO = \frac{\rho_{cyc} - \rho_w}{\rho_i - \rho_w} (V) A_p \quad (5)$$

where

PRO = production rate in m^3/hr

ρ_w = the water density in g/cm^3

ρ_i = the in situ sediment density in g/cm^3

V = the slurry velocity in m/hr

A_p = the discharge pipe area in m^2

The density and velocity data can be acquired with a laptop computer and be summarized and displayed over any time interval or in any format. Graphical and tabular summaries of variations in the average slurry density transported can indicate problems with changing site conditions such as sediment composition or size, variation in cutface height, obstructions in the channel, and increased digging depth. If the dredge is configured to operate in a fine sand, and coarse sand deposits are encountered, the increased suction and discharge line losses can be greater than the pump capability, thus significantly impacting production and efficiency. Variation in cutface height has a significant impact on production. Areas where the cutface height is minimal will have a decreased production rate. Obstructions in the channel or difficulties in dredging sediments more

consolidated that specified may require an alteration in cutterhead ladder positioning and swing rate, thus reducing the cycle efficiency. As more water is pumped in relation to sediment, the production will go down.

Dredge configuration problems can also impact the solids transported. Large suction pipe diameters require higher flow rates to insure that stationary deposits do not occur on the bed of the pipeline. If the discharge pipe diameter is significantly less than the suction pipe diameter, the high discharge velocities can generate head losses exceeding the pump capability, thus reducing solids transport. The pump performance is a function of resistance in the pipeline. If the piping is not correctly sized for the job, the pump may operate at a flow rate that will not sustain the sediments in suspension, with stationary deposits forming on the bed of the pipe. As the effective pipe diameter is reduced from the deposits, the flow rate is reduced even further to compensate for the increased resistance. If the pump is running at the maximum speed and cannot provide the additional head required, plugging of the pipe will occur resulting in extensive downtime.

To illustrate how dredge process data can be used along with predicted performance data, the following example is presented for a cutterhead dredge. The dredge has a 0.71-m- (28-in.-) diam suction line, 30.49 m (100 ft) in length, and a 0.61-m- (24-in.-) diam discharge line, approximately 991 m (3,250 ft) in length, with an 2.44-m- (8-ft-) lift to the disposal site. The digging depth in the channel was approximately 9.15 m (30 ft), and the sediments were composed of a medium sand with an in situ density of approximately 2.0 g/cm^3 (125 lb/ft^3). This dredge has a spud carriage for advancing the dredge with an estimated cycle efficiency of 75 percent.

The dredge model was run for the worst case scenario of a minimum bank height to cut, which results in an approximate overall dredge efficiency of 20 percent. By comparing the actual monitoring data to the worst case model data, the user can determine the minimum acceptable performance allowed by the contractor. The data for the six cutterhead cycles indicates that the dredge is performing at a higher efficiency than the minimum estimated efficiency of 20 percent. The computer model indicates for the worst case condition an average density while engaging the material of about 1.12 g/cm^3 (69.89 lb/ft^3), and an overall average cycle density of about 1.09 g/cm^3 (68.02 lb/ft^3) at a 20 percent overall dredge efficiency. The average of the monitoring data for all six cycles indicates an average density of 1.18 g/cm^3 (73.63 lb/ft^3) while engaging the material, and an overall cycle density of about 1.14 g/cm^3 (71.14 lb/ft^3). The average dredge model production is $643 \text{ m}^3/\text{hr}$ ($840 \text{ yd}^3/\text{hr}$) at the minimum efficiency, while the average actual dredge production was $1,000 \text{ m}^3/\text{hr}$ ($1,307 \text{ yd}^3/\text{hr}$). The average cycle efficiency for the dredge data is 77 percent, reflecting the use of the spud carriage method of advancement. For this example, the dredge productivity is substantially higher than predicted.

Hopper Dredge. The productivity of a hopper dredge is based on a number of factors. Hopper dredges are generally used to dredge free-flowing sediments such as sand or uncompacted fines, unless teeth are attached to the draghead to break up more consolidated materials. Therefore, a change in sediment characteristics can substantially reduce dredge production. The speed that a hopper dredge operates at can also influence productivity. When hopper dredges are operating in fine to coarse sand environments, they frequently overflow the hopper to maximize the load. The productivity of the overflow operation can be high if the discharge into the hopper is low enough to allow settling. If the discharge is too high, the turbulence in the hopper will maintain the solids

Table 1**Cutterhead Cycle Data - Actual and Estimated Slurry Density and Production**

Cyc	<i>C_{eff}</i>	<i>ρ_{mat}</i> g/cm³ (lb/ft³)	<i>ρ_{cyc}</i> g/cm³ (lb/ft³)	<i>ρ_{mat}</i> Model g/cm³ (lb/ft³)	<i>ρ_{cyc}</i> Model g/cm³ (lb/ft³)	<i>V</i> m/sec (ft/sec)	<i>PRO</i> m³/hr (yd³/hr)	<i>PRO</i> Model m³/hr (yd³/hr)
1	75	1.16 (72.38)	1.12 (69.89)	1.12 (69.89)	1.09 (68.02)	6.95 (22.8)	876 (1,145)	657 (859)
2	76	1.17 (73.00)	1.13 (70.51)	1.12 (69.89)	1.09 (68.02)	6.86 (22.5)	938 (1,226)	649 (848)
3	75	1.20 (74.88)	1.15 (71.76)	1.12 (69.89)	1.09 (68.02)	6.74 (22.1)	1,063 (1,389)	638 (834)
4	79	1.19 (74.26)	1.15 (71.76)	1.12 (69.89)	1.09 (68.02)	6.74 (22.1)	1,063 (1,389)	638 (834)
5	78	1.18 (73.63)	1.14 (71.14)	1.12 (69.89)	1.09 (68.02)	6.77 (22.2)	996 (1,302)	640 (836)
6	79	1.19 (74.20)	1.15 (71.76)	1.12 (69.89)	1.09 (68.02)	6.74 (22.1)	1,063 (1,389)	638 (834)
Avg	77	1.18 (73.63)	1.14 (71.14)	1.12 (69.89)	1.09 (68.02)	6.80 (22.3)	1,000 (1,307)	643 (840)

in suspension where they will overflow the hopper. Generally, hopper dredges employ low head, high capacity pumps because of short discharge line lengths. Conversely, cutterhead dredges must generate relatively higher discharge heads for the longer line lengths. The hopper dredge is therefore suction line limited on solids entrainment and transport. Suction line losses such as digging depth, drag head entrance loss, and sediment friction loss as well as the speed that the dredge operates will determine the concentrations of solids that can be transported.

Hopper Dredge Monitoring System Components. To monitor the effectiveness of solids entrainment and load production, a production meter (velocity and density gauge) can be used in conjunction with load and hopper volume measurement instrumentation (Scott 1993). The average density of slurry pumped into the hopper dictates the load production. The average density can be computed by both the density gauge and the combination of load and volume measurement. The average density in the hopper per load computed by the density gauge is computed by:

$$\rho_{load} = \frac{\sum_0^{N_{load}} \rho_s}{N_{load}} \quad (6)$$

where

ρ_{load} = the average load slurry density in g/cm³

ρ_s = measured slurry density in g/cm³

N_{load} = number of data points in load

The load and volume method of computing load density is accomplished by measuring the hopper volume in conjunction with the hopper load. The hopper volume can be measured by hand or through automated methods such as acoustic sensors. Traditionally, the hopper load is determined through pressure sensors. Bubbler tubes that vent in the keel of the dredge measure changes in hydrostatic pressure as the dredge drafts under load. The load is measured by relating the pressure changes to displacement of the dredge. The average density in the dredge is therefore computed as the change in volume over the change in displacement:

$$\rho_h = \frac{VOL_2 - VOL_1}{DISP_2 - DISP_1} \quad (7)$$

where

VOL_1 = volume of material in hopper before filling

VOL_2 = volume of material in hopper after filling

$DISP_1$ = displacement of dredge before filling

$DISP_2$ = displacement of dredge after filling

With the hopper dredge production computed by multiplying the percent solids in the hopper by the hopper volume or:

$$H_{pro} = \frac{\rho_h - \rho_w}{\rho_i - \rho_w} (H_{vol}) \quad (8)$$

where

H_{vol} = the load volume

ρ_w = water density

ρ_i = in situ sediment density

DISCUSSION: Both of the monitoring methods discussed have been automated by the Engineer Research and Development Center (ERDC) to provide real-time data and production/efficiency reports. Sensor data are acquired over a set time interval. Software computes the variables described by Equations 1-8 and provides graphical and tabular summaries. These data provide a real-time evaluation of dredge performance, with reports generated on a time-line determined by the user.

During the conduct of a dredging project, dredge performance can be affected by changes in site conditions such as unforeseen changes in sediment characteristics, foreign bodies in the waterway that impede progress, and inefficient dredge operation. Sediment characteristics in the project area may be substantially different than presented in the contract specification, thus affecting dredge performance. The sediments may be more consolidated or the sediment size may be greater than anticipated. In some cases, the digging depth or discharge pipe length may be excessive for the dredge design, thus limiting dredge performance. In all cases, delays in dredging are costly both to

the sponsor and the contractor. Frequently, the disputes that arise from changing site conditions involve a lengthy process of evaluating the legitimacy of claims. Without actual data from the dredge, defending or refuting claims is very difficult and time-consuming, oftentimes relying on questionable theoretical analyses. The availability of actual dredge process data can quickly show when and where impacts to the dredge operation occur, thus providing the necessary information to quickly settle the dispute and complete the project within time constraints. The initial capital investment in hardware and software to acquire, analyze, and display the data is minimal compared to the costs of lengthy disputes that oftentimes result in litigation.

CONCLUSIONS: Methods were presented for acquiring and reducing dredge process data for two types of dredge plant, a cutterhead pipeline dredge and a trailing suction hopper dredge. The quality of the data from these systems is dependent on the additional components of the monitoring system that were not discussed in any detail, the sensor installation and data acquisition design. Without careful installation and calibration of the sensors, and proper design of the data acquisition system, evaluating the dredge as a function of the dredge process data is not reliable.

The use of the monitoring systems previously discussed in conjunction with dredge performance models provides dredge contract administrators with additional tools for evaluating contractor performance in a fair and unbiased manner. The data provided by these systems can provide contract monitoring personnel with a real-time record of dredge performance throughout the duration of the dredging project.

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